TITLE OF INVENTION

DERIVATION OF COMPOSITE STEP-FUNCTION RESPONSE

BACKGROUND OF THE INVENTION

The present invention relates to distance to fault measurements, and more particularly to the derivation of a composite step-function response from band-limited channel frequency response in distance to fault (DTF) measurements.

For time domain reflectrometry (TDR) or distance to fault (DTF) transmission channel tests, step function testing along with impulse testing is often used to measure wave propagation and reflections of the transmission channel. The step-function test is useful when the transmission discontinuity is frequency selective. Due to its time domain integration nature, the step function response is more sensitive to low frequency components. In measuring frequency response of a system the measured frequency range may be band limited, such as between 25 MHz and 2.5 GHz.

Referring to Figs. 1a, 1b and 1c the respective graphs show the impulse response, the step function response, and a band limited step function response for a particular transmission channel. As readily seen, the step function response is very important in transmission channel diagnosis since the impulse response produces an almost insignificant difference where the reflection or discontinuity is a low frequency response, i.e., reflects low frequencies rather than high frequencies, while the step function produces a very noticeable difference as it contains mostly d.c. and low frequency components.

Generally the step function response may be derived by integrating the impulse response. As indicated above due to its integration nature, the step function response is more sensitive to low frequency components. For a frequency domain instrument, a transmission channel reflection coefficient is measured at each specified frequency within a specified range of frequencies, i.e., the measurement is band limited. TDR or DTF measurements are derived from the inverse Fourier transform (FFT^{-1}) of the channel reflection coefficient response. When a frequency domain instrument cannot make measurements at low frequencies, i.e., the source covers a frequency range that excludes the low frequencies, an incorrect step function response may be produced when the band-limited TDR response is integrated, as shown in Fig. 1c, especially if the discontinuity or reflection is low frequency selective.

What is desired is a method of deriving a composite step function response from a band-limited transmission channel response obtained from frequency domain measurements.

BRIEF SUMMARY OF THE INVENTION

Accordingly the present invention provides a method of deriving a composite step function response from a band-limited transmission channel frequency response. The method includes the steps of obtaining a time domain response from the band limited frequency response, identifying reflection events from the time domain response, estimating an impulse response from the identified reflection events, and determining the composite

step function from the estimated impulse response. The impulse response estimation is obtained from the observed time domain response as

$$y(n) = h(n) - h(n) \otimes w(n)$$

where y(n) is the observed time domain response, h(n) is the impulse response to be estimated and w(n) is a window function

$$w(n) = \mathbf{sin}(\omega_0 * n/F_s)/\pi n$$

where ω_0 is the initial frequency and F_s is the sample rate frequency. For reduction in calculation expense an impulse response segment is calculated over a narrow range of data about each reflection event. The resulting estimated impulse response is accumulated to produce the composite step response for the band limited transmission channel.

The objects, advantages and other novel features of the present invention are apparent from the following detailed description when read in conjunction with the appended claims and attached drawing.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWING

Figs. 1a, 1b and 1c are graphical views respectively of (a) an impulse response, (b) a step function response and (c) a band limited step function response for a transmission channel according to the prior art.

Fig. 2 is a graphical illustration view in the frequency domain of an estimated transmission channel impulse response algorithm according to the present invention.

Fig. 3 is a graphical illustration view in the time domain of the estimated transmission channel impulse response algorithm according to the present invention.

Fig. 4 is a plan view of a display of the composite step function in the band limited transmission channel according to the present invention.

DETAILED DESCRIPTION OF THE INVENTION

Referring to Fig. 1c it is apparent that the band limited step function response does not give a true step function response to the discontinuity event or reflection that exists at that point. Therefore in order to provide an accurate step function it is necessary to estimate the transmission channel impulse response. The step function response derivation, as described below, has four steps: distance to fault derivation from band limited channel response; reflection surface detection or identification, impulse response estimation and step function response calculation.

Distance to fault (DTF) is derived from reflection coefficients measured at discrete frequencies over a band limited frequency range. For computational efficiency and accuracy the following process is used, as an example:

For B being the measurement bandwidth and F_u the upper frequency edge, then a working bandwidth B_w is

$$U = \lfloor F_u/B \rfloor \text{ and } B_w = F_u/U$$

A new central frequency becomes $F_c = F_u - B_w/2$

and the lower frequency edge is $F_l = Fu - B_w$.

Down shift the frequency band $[F_l, F_u]$ to baseband ($F_c = 0$) and perform inverse discrete Fourier transform (IDFT or DFT^{-1}) using sample rate F_s equal to $2B_w$. This is equivalent to directly performing IDFT on frequency

data. Then up-convert to frequency $F_0 = B_w/2$ and extract the real part of the signal as the DTF signal.

In the digital domain this process may be simplified by letting $H(\omega_k)$ be a reflection coefficient at frequency ω_k ($k = 0, 1, \ldots, N-1$), $\omega_0 = 2\pi F_l$ and $\omega_{N-1} = 2\pi F_u$. Then

$$h(n) = (1/N)\Sigma_{k=0\to N-1} H(\omega_k)e^{j2\pi(k/2N)n} = \mathrm{IDFT}(2H,2N)$$

$$h_{DTF} = \mathbf{Re}(h(n))$$

$H(\omega_0) = 0, \ldots, H(\omega_{m-1}) = 0$ where $m=(F_u - B)N/B_w$.

The reflection surface identification may be automatic or user-interactive. In user-interactive mode a user inputs a center location $(i_1 + i_2)/2$ or the edges of the impulse response. In the automatic mode the center location is detected based on the event's reflection magnitude in the time domain.

A detection function $A(n)$ may be an envelope value of the up-converted signal $h(n)$

$$A(n) = |h(n)|$$

Alternatively using the local energy of the baseband signal as the detection function,

$$x(n) = |h(n)|\mathrm{sign}(h_c(n)), \qquad A(n) = \Sigma_{m=-K\to K}x(n-m)$$

where $h(n) = h_c(n) + jh_s(n)$. In either case if $|A(n)|$ is greater than a threshold, then a reflection surface is detected and the center location determined.

For impulse response estimation let $h(n)$ denote the impulse response to be estimated and $y(n)$ the corresponding band limited response ($y(n) = h_{DTF}(n)$). Looking at Fig. 2 in the frequency domain $Y(\omega) = H(\omega) - H(\omega)W(\omega)$,

where $Y(\omega)$ represents the band limited frequency coefficients, $W(\omega)$ is a window function representing the frequency range not covered by the band limited source and $H(\omega)$ is the combination of the measured frequency coefficients and the frequency coefficients estimated over the window. In the time domain this becomes

$$y(n) = h(n) - h(n) \otimes w(n) = h(n) - \Sigma_m h(m)w(n-m)$$

the window function being $w(n) = \mathbf{sin}(\omega_0 n/F_s)/\pi n$ where F_s is the sampling frequency. As seen, the observed time response $y(n)$ is a linear function of the impulse response $h(n)$. Since $y(n)$ may have many data points, it may be computationally expensive if every impulse response point is estimated. However normally each reflection surface covers a very short distance and its response lasts a limited time. Therefore for each identified reflection surface the impulse response is estimated over a narrow range of data around the reflection surface, as illustrated in Fig. 3.

$$y(n) = \begin{cases} -\sum_{m=i1->iM} h(m)w(n-m) & n_1 \le n < i_1 \\ & i_2 < n \le n_2 \\ h(n) - \sum_{m=i1->iM} h(m)w(n-m) & i_1 \le n \le i_2 \end{cases}$$

In matrix form this is

$$
\begin{vmatrix} y(n_1) \\ \vdots \\ y(i_1-1) \\ y(i_1) \\ y(i_1+1) \\ \vdots \\ y(i_2) \\ \vdots \\ y(n_2) \end{vmatrix}
\begin{vmatrix} -w(n_1-i_1) & -w(n_1+1-i_1) & \ldots & -w(n_1+M-1-i_1) \\ \vdots & & & \\ -w(-1) & -w(-2) & \ldots & -w(-M) \\ 1-w(0) & -w(-1) & \ldots & -w(1-M) \\ -w(1) & 1d-w(0) & \ldots & -w(2-M) \\ \vdots & \vdots & & \vdots \\ -w(i_2-i_1) & -w(i_2-i_1-1) & \ldots & 1-w(0) \\ \vdots & \vdots & & \vdots \\ -w(n_2-i_1) & -w(n_2-i_1-1) & \ldots & -w(n_2-i_2) \end{vmatrix}
\begin{vmatrix} h(m_1) \\ h(m_2) \\ \vdots \\ h(m_M) \end{vmatrix}
$$

The localized h(m) may be optimally resolved by applying least-square error criteria.

$$\mathbf{Y = DH, \qquad H = (D^TD)^{-1}D^TY}$$

The final step function response is calculated by accumulating the impulse response.

$$x(n) = h(n) \otimes u(n) = \sum_{m=-\infty->\infty} h(n-m)u(m)$$

where u(n) is the step function

$$u(n) = \begin{cases} 1 & n \geq 0 \\ 0 & n < 0 \end{cases}$$

This produces

$$x(n) = \sum_{m=0->n} h(n-m)$$

Typical results of the band limited method described above are shown in Fig. 4 which shows the estimated impulse and step function responses of a band limited channel. The lighter line represents the estimated impulse response **20**, showing an apparent small reflection **22** at approximately 200

meters and a larger negative impulse **24** at approximately 400 meters. The corresponding step function response **30** shows a significant response **32** at 200 meters and a less significant response **34** at 400 meters. The combination of these responses gives a more complete picture of the events that occur in the transmission channel.

Thus the present invention provides a method of deriving a composite step function response from a band limited transmission channel frequency response in distance to fault measurement by estimating the impulse response from the measured frequency response and a window for the excluded frequencies, and accumulating the impulse response to obtain the step function response.